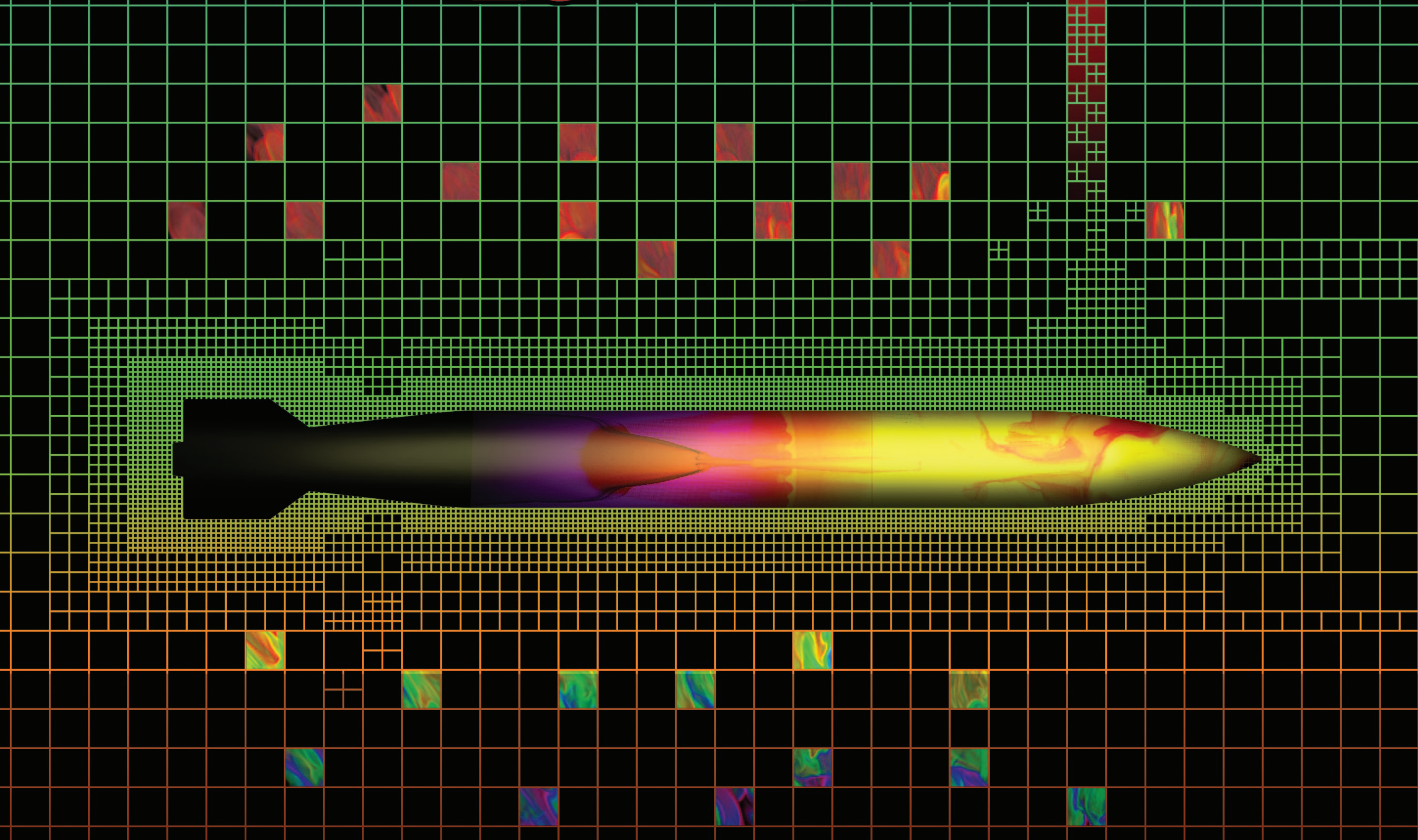
But will it work?



The threat is real. The security challenges confronting the United States in the 21st century are complex and multifaceted, and they demand the best science, technology, and engineering.

North Korea, despite international sanctions, continues to pursue both nuclear-weapon and ballistic-missile technology. On January 24 of this year, following action by the United Nations condemning the December launch of a missile, the North Korean Defense Commission issued the following statement: "We are not disguising the fact that the various satellites and long range rockets that we will fire and the high level nuclear test we will carry out are targeted at the United States."

Shortly thereafter, North Korea conducted its third nuclear weapons test.

Equally intransigent, Iran recently informed the International Atomic Energy Agency that it would introduce new centrifuges to its main uranium enrichment plant near Natanz. The new IR-2m units will allow Iran to enrich uranium at higher rates.

What could go wrong with a nuclear bomb or warhead?

Will It Work?

The end of the Cold War marked a turning point in how the United States maintained the safety, security, and reliability of its nuclear deterrent. From 1945 until 1992, the United States routinely replaced nuclear weapons with new systems that had been designed, tested, and fielded using a series of simulations, experiments, and tests at the laboratories, including underground nuclear weapons tests in Nevada. That stopped with the last underground test (Divider) on September 23, 1992.

So what could go wrong with a nuclear bomb or warhead? The nation has maintained nuclear weapons for more than half a century, so we must know all there is to know. After all, they are pretty much just an explosive with a detonator system inside a metal casing, right?

Not Just Another Bomb

Compared with that of conventional weapons, the effectiveness of modern nuclear weapons is a remarkable feat of physics and engineering; nuclear weapons have the almost unbelievable capability, using plutonium and uranium, to convert a few pounds of these elements into the explosive equivalent of thousands or millions of tons of TNT. This is about 100 times more destructive power than was released by the bombs that devastated Hiroshima and Nagasaki.

To achieve this kind of yield while meeting demanding safety and security standards is not easy. The complexity of a nuclear weapon is profound. Whereas conventional bombs and warheads use a simple design of a high explosive and a relatively simple detonator, nuclear weapons use complicated, high-precision mechanisms.

By itself (not including its delivery system, such as a missile), a nuclear weapon consists of many thousands of highly engineered, precision-crafted components, including complex electrical systems. Components can be made of steel, aluminum, silicon, and even plastic. These components must be made small enough and precise enough so that once assembled, the entire system will fit inside an 11.5-foot-long by 1-foot-diameter bomb or so that several can ride inside the nose cone of a missile. To manage this feat, components are sometimes manufactured to tolerances many times smaller than a human hair.

More to the point, to be successful, the interactions of the weapon components have to mesh precisely to initiate the most complex of *natural physical processes* and to stimulate them to work together, synergistically. These complex processes include chemistries, solid-state physics, plasma physics, and nuclear and thermonuclear reactions—the energy source of the Sun and stars.

Individually, many of these components and processes are far from being completely understood, even today. How and why these all work together to create a successful nuclear weapon explosion remains elusive.

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Weapons with Crow's Feet

The nuclear weapons in the U.S. stockpile were designed and built to be replaced with new designs and builds every 10 to 15 years, or sooner if the U.S. defense strategies required it. Now these weapons have lived beyond their expected lifespans, and their components continue to age.

Over time, plastics become brittle and break down, releasing gases. Electronic systems based on antiquated technologies like vacuum tubes and plastic-coated copper wire corrode. Adhesives bonding key components weaken. Metal coatings naturally deteriorate. Metals and metal joints corrode and weaken. Vibrations from transportation and deployment further impact components. Many of these issues are faced by every car owner. With years of environmental changes in temperature, pressure, and humidity, and in the presence of radioactive elements like plutonium and uranium, components degrade and may eventually fail to work.

In short, aging materials change and in so doing, change their physical, chemical, and mechanical properties; aged materials no longer behave as they once did. New behaviors can be unpredictable.

Nuclear weapons must work, and perfectly, *only* if the president of the United States has authorized their use—and they must *never* work if the president has not authorized their use. Can an aging stockpile meet these demanding requirements?

For example, using hypotheses, theories, and experimental trial and error, the swordsmiths of feudal Japan learned that when specific combinations of high- and low-carbon steel, along with other materials, were precisely processed by controlling temperature and carefully folding, welding, and quenching them, a superior sword was born: the katana, a.k.a. the samurai sword, the most feared and revered weapon of their time. They did not fully understand *why* these materials and processes worked in this way, but they could describe what materials to use and explain how to process them, and they could predict a consistent outcome. For the job at hand, this level of knowledge was sufficient.

Scientists could say with some confidence that they understood some of the weapon physics. But by no means did they claim to understand all of what they did and saw.

But explaining and predicting phenomena using testing does not necessarily mean *understanding* phenomena.

Turning Knobs

Real-world trial-and-error experimentation is sometimes called the "engineering approach" because it uses hands-on building and testing of theoretical concepts. This was largely the approach by which nuclear weapons were invented and by which they evolved for 47 years. Like Japanese swordsmiths, weapons scientists hypothesized, theorized, and experimented, using this and trying that with different materials, processes, and designs in very successful efforts to meet the requirements established by the U.S. military.

For the job at hand, this level of knowledge was sufficient and was codified in weapon simulation computer programs. A deeper understanding was certainly desired and sought out, but it was not necessary in order to accomplish the Cold War mission. Regardless, better tools were needed to better understand thermonuclear weapons.

Still, scientists' ability to explain and predict weapons phenomena got stronger, and an amazing body of knowledge grew, so they could say with some confidence that they understood some of the weapon physics. But by no means did they claim to understand *all* of what they did and saw. In fact, it was not uncommon for test results to contradict scientists' best predictions and call into question what they thought they understood.

The nation needed a new way to assess the stockpile. The answer would be the science-based Stockpile Stewardship Program.

When reality did not match their predictions, the scientists were often forced to adjust their calculations until these matched test results, but without really understanding why these adjustments worked. It was like the early days of radio, when the scientists and engineers understood the principles of the device but lacked the predictive power to design the radios to respond exactly. Radio response was "tuned" (often by turning a knob) to achieve the final high-precision match required so that radio transmitters and receivers could work together. Indeed, the practice by nuclear scientists of massaging calculations until they fit their real-world test results was called "turning knobs." The knobs were embedded in the weapon simulation computer codes. Thus, testing was done not only to see if a weapon worked, but also to try and eliminate particularly troubling knobs by gaining a better understanding of the weapon physics.

But then real-world underground testing in Nevada and deployment of new systems went away. What would take their place? Would the military retain confidence in systems aboard the submarines and planes and in missile silos? Could the president be assured that systems were safe, secure, and effective? Would allies and adversaries be convinced of the effectiveness of America's nuclear deterrent?

The Dilemma

This was a huge dilemma facing the nation in the early 1990s. Members of the president's cabinet, members of Congress, the scientists at the three national security science laboratories (the Los Alamos, Lawrence Livermore, and Sandia national laboratories), and military leaders debated whether it was wise to end weapons development and underground nuclear testing without having a satisfactory alternative in place. Without new production and with a ban on underground testing, the nation needed something to ensure that stockpiled weapons would continue to work into the future, perhaps for decades. In other words, the nation needed a new way to assess the stockpile. The answer would be the science-based Stockpile Stewardship Program (SSP).

Today the SSP is applying the best experimental, computational, modeling and simulation, and engineering capabilities to provide the scientists and engineers at the laboratories with the tools to understand what is happening to the nation's deterrent. These tools are allowing the laboratory directors to successfully execute life-extension programs in support of Navy and Air Force systems, to resolve issues that arise in these aging nuclear systems. At the end of each fiscal year, the laboratories are required by law to report to the president of the United States, through the secretaries of Energy and Defense, on the state and health of the nation's deterrent.

Supercomputer Simulations

From the beginning of the Manhattan Project, Los Alamos has relied on experimental data and weapon simulations running on state-of-the-art computers when designing weapons. During the Cold War the national security laboratories continued to use the most powerful and advanced computers for weapons simulations. The Department of Energy's Accelerated Strategic Computing Initiative (ASCI) program—now called the Advanced Simulation and Computing (ASC) program—was established in 1995 as a pillar of the Stockpile Stewardship Program (SSP). The goal was to enable high-resolution 3D simulations of nuclear weapons by 2005. The idea of executing high-resolution 3D simulations of a nuclear weapon was, in 1995, revolutionary.

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Computing science in the early 1990s was not up to the task. This was the era of floppy discs, Apple's Newton and Macintosh computers, and Windows 95. In fact, the notion of being able to build computers that had the power, speed, and memory needed to accurately model and simulate a nuclear weapon explosion from first principles, much less in 3D, was thought nearly impossible by many.

For example, a standard unit of computer speed and power is floating-point operations per second (flops). An initial calculation done at this time by Lawrence Livermore National Laboratory concluded that more than 100 teraflops (*100 trillion* flops) would be required to execute the high-resolution 3D simulations, with sufficient accuracy, for the SSP. But at the time, Livermore's most powerful computer provided only 13.7 gigaflops (*13.7 million* flops). This meant that its computing power would need a 7,000-fold increase in less than a decade, implying a technological growth rate many times that given by Moore's Law—the industry standard for predicting increases in computing power. To run the models and simulations then envisioned, the laboratories needed significantly larger, faster, and more powerful computers than Moore's Law allowed.

High-resolution 3D weapons simulations would require vast leaps in supercomputer design, development, programming, and computing power. It would also require unprecedented levels of electric power. This meant needing large new infrastructures to provide power and cooling.

Avatars Won't Work

It may be difficult for most people to grasp the difficulty of creating 3D simulations for the SSP. After all, computer-generated 3D graphical representations of nuclear events can be made for the movies. Hollywood produces simulations that *appear* to be real but do not need to reflect reality; in contrast, the SSP needs simulations that reflect how nature really works. Weapons scientists must produce a high-resolution representation of real events, as nature would unfold them.

To accomplish this, they must rely on the quality and accuracy of their experimental data, models, and programs. There is no tolerance for any "garbage in, garbage out" dynamic in nuclear weapons science**.** Whenever possible, those elements have been rigorously tested—and verified with the highest levels of confidence and validated against experimental data—before being used in simulations that will represent the real world.

A Choice of One

Despite the challenges of developing the advanced computing platforms and the codes, there was no other choice. The scientific basis for assessing the stockpile is formed by the ASCI tools, in partnership with new experimental tools like the Dual-Axis Radiographic Hydrotest facility at Los Alamos and the National Ignition Facility at Livermore, and with data from the more than 1,000 nuclear weapons tests conducted by the United States up until 1992.

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The demands of the SSP and the evolution of the ASC would eventually make computer modeling and simulation *an integral part* of science in general, changing the centuries-old way of doing science. Even for fields of science that can still perform real-world testing, virtual-world computer modeling and simulation have become a normal part of the scientific process. Today, computer simulations are a regular, key element—alongside theory and real-world testing—of practicing the scientific method.

The SSP is a successful and evolving effort that continues to push the state of the art. Incredibly, in 2005, the 100-teraflops goal was reached. But the SSP's supercomputing needs were *vastly* underestimated. Consequently, in 2008, Los Alamos unveiled the world's first petaflop (1.0 *million billion* flops) supercomputer, Roadrunner. Since Roadrunner, another petascale machine, Cielo, has come online at Los Alamos, and Livermore has stood up Sequoia at almost 16 petaflops. Los Alamos is proceeding with Trinity, a 30- to 40-petaflop machine. The machines at Los Alamos and at Livermore are working 24 hours a day, 7 days a week, 365 days a year. The demand for time on these and other machines by scientists is never-ending.

The SSP has successfully resolved problems related to aging, even problems in the original designs and manufacturing of some weapons, and has enabled corrections. It has made the life-extension programs for weapons a success. It has successfully resolved the need for some knobs in the weapon codes. It has provided simulations of nuclear weapons and their subsystems in 3D. It is important to understand that these 3D simulations are often referred to as "hero calculations," given the amount time (weeks, months, and in some cases, years) required to set up the code and run the calculation, even on petascale machines.

Supercomputers and the weapon codes have played a key role in all these successes. They will become even more important as the stockpile continues to age and the nation continues its moratorium on conducting real-world, full-scale tests.

Supercomputer simulations have allowed scientists and engineers to discover phenomena previously hidden to real-world experimentation, making it necessary to ask more questions, change some theories, and explore new directions. As a result, the need for high-resolution 3D simulations is clear. Indeed, some weapons issues can be accurately addressed *only* in 3D. However, high-resolution 3D simulations require vastly more powerful supercomputers than 2D simulations do.

Bigger Than Manhattan

To help put the SSP effort into perspective, it took almost $26 billion in today's money and two years for the scientists of the Manhattan Project to build the first atomic bombs, relatively simple devices compared with today's deterrent. But to understand how and why the weapons work remains a work in progress; the nuclear weapons community continues to pursue a complete understanding of nuclear weapons, almost seven decades after the Manhattan Project ended.

When the nation and our allies are banking on the reliability, safety, and security of the aging nuclear deterrent to protect them from ever more dangerous and unpredictable aggressors—but without detonating a weapon to absolutely, positively know the stockpile works—is there ever enough science to be done? As the stockpile shrinks and ages and as weapons rely more on replaced and rebuilt components, more questions come to the surface, and more science, not less, is required for future annual assessments.

In a world without continued real-world testing, experimental data coupled with high-performance computing, modeling, and simulation are *the* game in town.

The SSP is reliant on supercomputing, and the SSP is the *only* way to answer the question, *But will it work?*

~Clay Dillingham